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Strain Rate Strengthening and Failure Behavior of Filament Wound Composites

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COVER SHEET

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Title: **Strain Rate Strengthening and Failure Behavior of Filament Wound Composites**

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ABSTRACT

Strain rate strengthening of fiber reinforced composites under axial compression has been observed and reported previously in the literature for simple composite systems. In an effort to improve the rate dependent predictive capabilities of existing strength models, experiments exploring the intermediate strain rate failure behavior of composite structures under axial compression are discussed. A multi-axis, scaled-up specimen design for filament wound carbon fiber/epoxy composite tubes introduces complexity due to off-axis fibers and stiffness mismatch between plies, as well as dynamic issues including stress equilibration and inertial effects. Initial results from our focused study aimed at revealing the strain rate dependent role of off-axis fiber angle on the failure mechanism of these complex specimens are discussed herein.

INTRODUCTION

Composite materials offer strong, lightweight solutions to structural design, driving their use in high performance, dynamic applications space. Advancements in composites processing methodologies facilitate more complex fiber composite architectures and designs which, in turn, demand more rigorous predictive capabilities.

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An effort to improve our current composite materials model predictions at elevated temperatures and strain rates has prompted experimental investigations on strain rate strengthening in full-sized composites with complex fiber architectures and microstructural inhomogeneities.

Strain rate sensitivity has been well-documented in polymers [1] and fiber reinforced polymers [2] at the coupon level and observed in-house in full-sized composite structures. In contrast to the number articles reporting a corresponding increase in strength with applied strain rate Jacob et al. [3], there have been a dearth of studies which discuss this phenomenon in depth in composite materials. Despite this, the following polymer strain rate strengthening mechanisms have been proposed over the past three decades.

- Molecular chain inertia [2]
- Changes in fracture propagation [4],[5]
- Brittle-ductile transition, secondary relaxation [6],[7]

Each of these mechanisms may serve to prevent fiber microbuckling in composite structures, thus increasing the stress required for compressive failure to occur. While molecular chain inertia and fracture propagation (thermal or plastic blunting, see [8]) are important to consider, brittle-ductile transition of the polymer matrix is of particular interest due to a recent study by Kendall and Siviour [9].

The brittle-ductile transition in epoxy resin is synonymous with its β phase transition, which occurs around -50°C and is attributed to the relaxation of hydroxy-ether groups and other parts of the network structure [10]. Mulliken and Boyce [11] demonstrated the effect of applied strain rate on the α and β phase transitions in polycarbonate and poly(methyl methacrylate) (PMMA), observing that the β phase transition exhibited a significant strain rate dependence (i.e., $25.2^{\circ}\text{C}/\text{decade}$ strain rate in PMMA). Extrapolations based on temperature-strain rate equivalence by Jordan et al. [12] led them to postulate that the β phase transition is shifted to room temperature at strain rates of $\sim 7000\text{ s}^{-1}$ in polyvinyl chloride. The incorporation of carbon fibers has been shown to further increase the β transition temperature in epoxy from -50°C to -30°C ; this has been attributed to interactions between the epoxy macromolecules and molecules at the fiber surface [13].

Kendall and Siviour [9] demonstrated equivalent stress-strain behavior for poly(vinyl chloride) tested at low temperatures and high strain rates and concluded that this equivalence could be used to simulate high strain rate experiments using cold quasi-static testing. The authors further postulated that, if extended to composite materials, this approach would allow detailed in situ failure analyses typically precluded by high strain rate evaluation.

Of particular interest to us is the role of strain rate strengthening and its effect on multi-axis parts. Bing and Sun [14] performed experiments which highlight the necessity in characterizing and understanding the effect of strain rate on composite failure behavior. Under compressive loading, the same composites (off-axis fiber angle of 15°) experienced different failure mechanisms as a function of strain rate (i.e., microbuckling failure at 10^{-5} s^{-1} and matrix shear failure at 10^{-1} s^{-1}) [14].

Our objective is to evaluate the compressive response of composite tube specimens across quasi-static and intermediate strain rates with the aim of identifying (1) whether significant strain rate strengthening occurs below 10^2 s^{-1} in these composites, (2) compressive failure mechanisms and any effect of loading rate on such and (3) the role of each ply. Preliminary results are discussed herein.

MATERIALS AND METHODS

Composite specimens

Composite specimens were prepared via filament winding of carbon fiber (Tenax®-E HTS40 F13 12K, Toho Tenax America, Inc.) and epoxy resin (EPIKOTE™ Resin 862/EPIKURE™ Curing Agent W, Momentive, Inc., 100:26.4 wt% mixing ratio) in a $[\pm 12, \pm 45, \pm 12, \pm 80]_2$ and $[\pm 12, \pm 45, \pm 12, \pm 70]_3$ pattern (2 in ID, 3 in long). The specimen length was sufficient to capture cross-overs in each wind angle. Dogbone-shaped cylindrical specimens were prepared using a composite overwrap to prevent end brooming during compressive loading (Figure 1); these specimens possessed an overall length of 5 in, leaving a 3 in gage section.

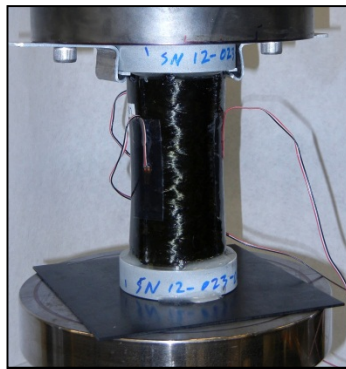


Figure 1. Filament wound composite tube (2 in ID, 3 in gage length).

Quasi-static testing

Quasi-static experiments were performed using a servo-hydraulic testing machine (500 kip, MTS Systems Corporation) at 0.01-0.05 in/min. Strain was measured using three extensometers placed at the center of the specimen gage section of the tube, each at a diametrical spacing of 120°. Prior to testing, the specimen was sandwiched with aluminum end caps (3/4 in thick, 4 in diameter); these prevented brooming by deforming plastically at the fiber/aluminum interface, providing a constraint to radial expansion.

Intermediate rate testing

A servo-hydraulic testing machine (200 in/s stroke, MTS Systems Corporation) was used to evaluate the composite specimens at elevated strain rates (10^1 - 10^2 s⁻¹). Composite tubes were placed between aluminum 6061 end caps (3/4 in thick) which underwent plastic deformation local to the region in contact with the tube ends, providing a radial force acting against end brooming. Frequency domain digital signal processing was used to mitigate oscillations in the load response acquired using a quartz load cell. Strain measurements were acquired using three strain gages in lieu of extensometers and end caps served the same purpose as in the quasi-static experiments.

RESULTS

Strain Rate Strengthening

The filament wound composite tube specimens experienced an increase in compressive strength at intermediate strain rates (Figure 2), consistent with prior investigations into orthogonal systems [2].

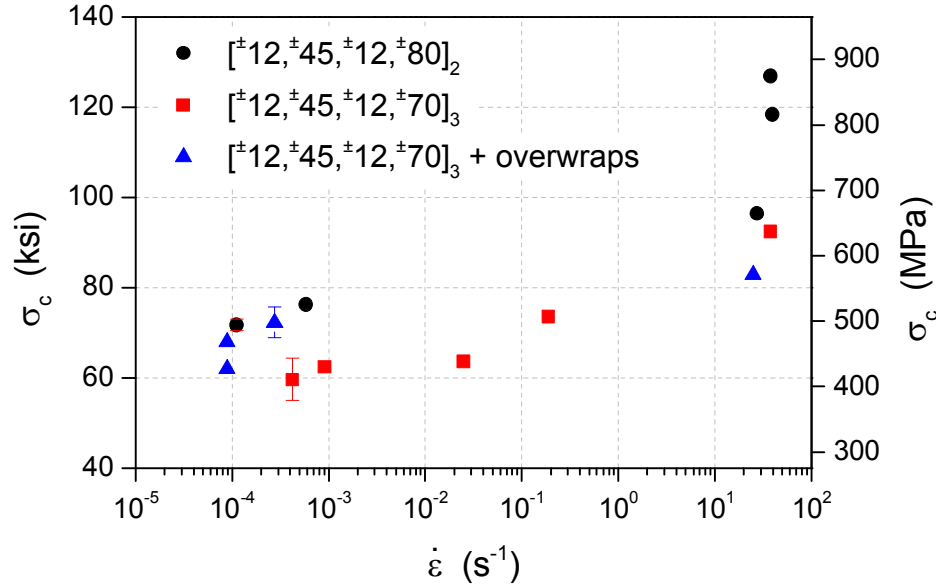


Figure 2. Stress-strain rate response of composite tubes; error bars represent confidence on mean with a difference of means of 95%.

Failure Behavior in Complex Winds

End brooming failure and end initiated helical failure was eliminated at both quasi-static and intermediate strain rates with the use of filament wound overwraps. Based on quasi-static compressive results (Figure 3), failure initiation/progression has no statistical effect on composite strength.

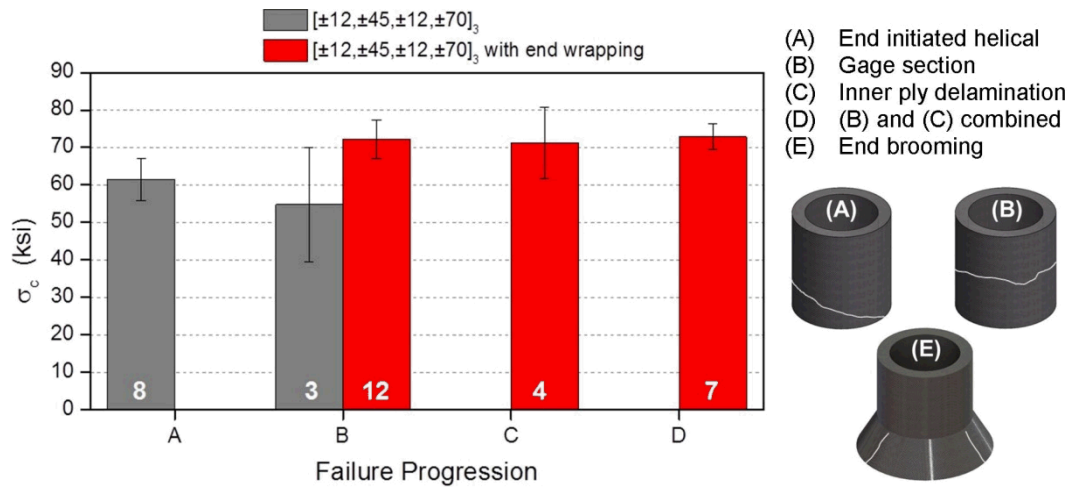


Figure 3. Strength and number of specimens exhibiting four different failure behaviors; error bars represent confidence on mean with a difference of means of 95%.

Failure Mechanism

Prior reports on the compressive behavior of unidirectional composites indicate that composites with fibers oriented $>15^\circ$ off axis fail due to matrix shearing, rather than fiber microbuckling [14]. In filament wound composites, all plies are off-axis and each off-axis ply plays a critical role in the mechanical performance. While the low angle fibers (i.e., 12°) are expected to carry most of the axial compressive load, off axis (i.e., 45° and 70°) layers prevent structural failure of the tube which could otherwise occur without fiber failure in a purely low-angle tube [15]. This coupling is evident in our specimens; here, we observe kinking in the 12° and 45° layers (Figure 4).

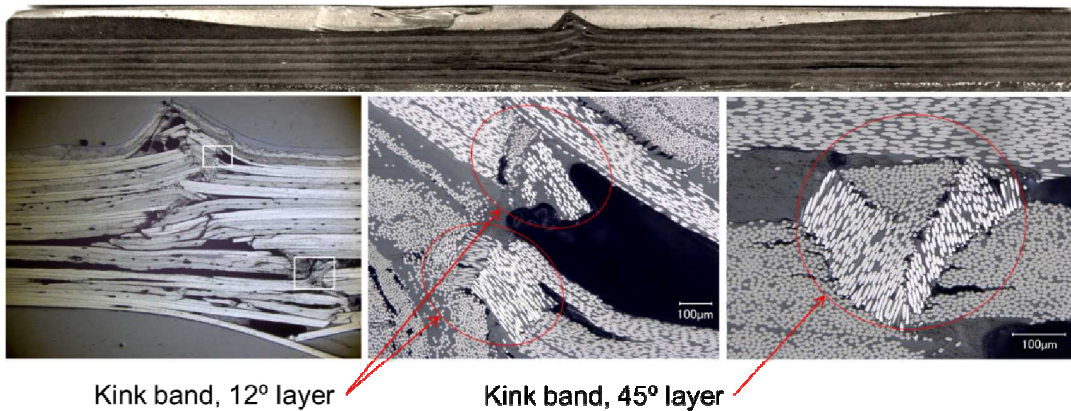


Figure 4. Delamination, cracking and microbuckling upon compressive failure at intermediate strain rate.

CONCLUSIONS

Filament wound composite tubes evaluated at strain rates $<10^2 \text{ s}^{-1}$ exhibit strain rate strengthening under axial compressive loading. While there is substantial literature describing the epoxy matrix brittle-ductile transition and its role on strain rate strengthening, further efforts to characterize this transition in our epoxy system and to identify the strain rates at which this transition occurs at room temperature are necessary.

Future efforts in intermediate strain rate characterization are contingent upon adopting a transmission bar approach [16] to circumvent oscillations in the testing frame from impinging on measured force data. This effort will focus on understanding the role of each composite ply on compressive failure through the evaluation of filament wound tubes with primarily low angle (12°) and high angle (45° and 70°) ply reinforcement.

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REFERENCES

1. Siviour C.R. and J.L. Jordan. March 2004. "A miniaturized split Hopkinson pressure bar for very high strain rate testing," Air Force Research Laboratory Technical Report, AFRL-MN-EG-TR-2005-7014.
2. Groves, S.E., R.J. Sanchez, R.E. Lyon and A.E. Brown. 1992. "High strain rate effects for composite materials," in the *11th ASTM Symposium on Composite Materials: Testing and Design*, Pittsburgh, PA. May 4-5.
3. Jacob, G.C., J.M. Starbuck, J.F. Fellers, S. Simunovic, and R.G. Boeman. 2004. "Strain Rate Effects on the Mechanical Properties of Polymer Composite Materials," *Journal of Applied Polymer Science*, 94:296-301.
4. Kistner, M.D. December 1990. "Strain rate sensitivity of polymer-matrix composites under mode I delamination," Wright Research and Development Center Technical Report, WRDC-TR-90-4121.
5. Williams, J.G. 1977. "Fracture mechanics of polymers," *Polymer Engineering and Science*, 17(3):144-149.
6. Christensen, R.M. 1982. *Theory of Viscoelasticity: An Introduction*. Academic Press, New York.
7. Gómez-del Río, T. and J. Rodríguez. 2012. "Compression yielding of epoxy: Strain rate and temperature effect," *Materials and Design*, 35:369-373.
8. Low, I.M. and Y.W. Mai. 1989. "Rate and temperature effects on crack blunting mechanisms in pure and modified epoxies," *Journal of Materials Science*, 24:1634-1644.
9. Kendall, M.J. and C.R. Siviour. 2013. "Experimentally simulating adiabatic conditions: Approximating high rate polymer behavior using low rate experiments with temperature profiles," *Polymer*, 54:5058-5063.

10. Ochi, M., M. Yoshizumi and M. Shimbo. 1987. "Mechanical and dielectric relaxations of epoxide resins containing the spiro-ring structure. II. Effect of the Introduction of Methoxy Branches on Low-temperature Relaxations of Epoxide," *Polym Sci Part B: Polym Phys*, 25(9):1817-1827.
11. Mulliken, A.D. and M.C. Boyce. 2006. "Mechanics of the rate-dependent elastic-plastic deformation of glassy polymers from low to high strain rates," *Int J Solids Struct.*, 43:1331-1356.
12. Jordan J.L., C.R. Siviour and B.T. Woodworth. February 2013. "High strain rate tensile and compressive effects in glassy polymers," Air Force Research Laboratory Interim Report, AFRL-RW-EG-TP-2013-006.
13. Gong, X. 1998. "The dynamic mechanical behavior of random-in-plane short fiber-reinforced epoxy resin composites," *Polymers for Advanced Technologies*, 7:141-145.
14. Bing Q.D. and C.T. Sun. 2005. "Modeling and testing strain rate-dependent compressive strength of carbon/epoxy composites," *Composites Science and Technology*, 65:2481-2491.
15. Peters, S. T., ed. 2011. *Composite Filament Winding*. ASM International, pp. 107.
16. LeBlanc, M.M. and D.H. Lassila. 1995. "A hybrid technique for compression testing at intermediate strain rates," *Experimental Techniques*, 20(5):21-24.